An Energy-Optimal Scheme for Neighbor Discovery in Opportunistic Networking

Dongmin Yang, Jongmin Shin, Jeonggyu Kim, Cheeha Kim
Department of Computer Science and Engineering,
Pohang University of Science and Technology (POSTECH),
790-784 San 31, Hyoja-Dong, Nam-Gu, Pohang, Gyungbuk, Korea
Email: {likeba, sjm0621, haji1202, chkim}@postech.ac.kr

***Abstract*—In opportunistic networking, networks are sparse and nodes are moving around, so it is hard to predict when a node gets and how long it keeps in contact with another. For prompt neighbor discovery, a node is assumed to broadcast continuously probing messages to discover another in its vicinity. This kind of persistent probing consumes too much energy for battery-operated devices to afford. One way to save energy for neighbor discovery is simply to turn off radio during non-contact time. In this paper, as the first step toward the general solution, we simplify the problem consisting of one sender and one receiver moving around and present a novel neighbor discovery scheme with radio "on" and "off" which is optimal in a sense that it does not miss a contact with the minimum energy consumed.**

I. INTRODUCTION

Opportunistic networking is an emerging technology with a wide range of potential applications (e.g., Bluetooth, Zigbee), where most devices (e.g., PDAs, UMPCs, laptops, cellular phones) are battery-operated so that their radio coverage is limited and data is exchanged only through contacts which infrequently occur [1]. Furthermore, they cannot afford persistent probing to discover neighbors in contact. As a feasible solution, it is effective to turn off radio, so called sleeping mode, during non-contact time and to turn it on only for neighbor discovery and data exchange. It is not trivial to predict accurately when nodes encounter and how long they keep in contact, while it is important to find such figures for successful data exchange.

In other applications [2], [3], energy saving schemes employing sleeping mode can be found. However, in the researches for neighbor discovery [4], [5], [6], the sleep mode for energy saving is not counted at all.

Since data is opportunistically exchanged, it may cause unexpected long delay to fail discovering neighbors. Generally speaking, to discover a neighbor (see Fig. 1), node S, which has data to send, broadcasts probing messages (so called probing mode) and node R, which is supposed to receive data from node S, keeps listening to probing messages (so called listening mode). When node R receives a probing message, it will respond to node S and receive data. To save energy, nodes S and R are allowed to sleep when they believe they are not in contact. When we assume all nodes have some data to send, it is straightforward to imagine that every node acts identically. That is, it must be in one of three modes, probing, listening, and sleeping. However, in this paper, as the first step toward the general solution, we consider the case shown in Fig. 1 and obtain its optimal solution using analytical exploration of total energy consumption. In other words, the optimal neighbor discovery scheme guarantees the minimum energy consumption and neighbor discovery within delay bound D, if user mobility is modeled as a stochastic process. Delay bound D is defined as the upper bound on discovery delay, time difference between the instant of discovering contact and the beginning instant of physical contact. The delay bound can be derived from the distribution of contact duration and required data communication time [5], [7]. If two nodes in physical contact discover each other in less than D, they will succeed in data exchange.

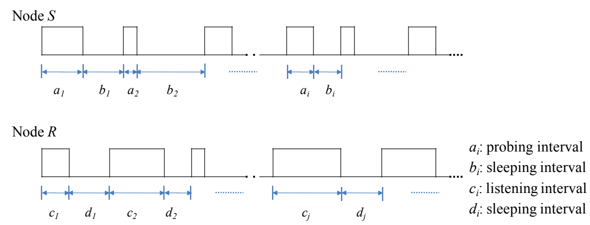

Fig. 1. Listening and probing sequence including sleeping mode

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II. PROBLEM STATEMENT

For simplicity of illustrating neighbor discovery process, we use Fig. 1 where node S keeps probing and node R keeps listening. Node S sends probing messages for interval a_i and then sleeps for interval b_i. Similarly, node R listens to receive probing messages for interval c_j and then sleeps for interval d_j. Note that these intervals may be determined arbitrarily according to a scheduling policy. Let E_P, E_L, and E_S ($E_P > E_L \gg E_S$) denote respectively the energy consumed in probing, listening, and sleeping mode. Then, the total energy E_{total} can be expressed as

$$E_{total}=\sum_{i=1}^{M}(E_P \cdot a_i+E_S \cdot b_i)+\sum_{j=1}^{N}(E_L \cdot c_j+E_S \cdot d_j).$$

Without loss of generality, we can assume that node S and node R operate for interval T such that $\sum_{i=1}^{M}(a_i+b_i) = \sum_{j=1}^{N}(c_j+b_j) = T$. Given D, the problem is to find how to schedule probing and listening for neighbor discovery with the minimum energy. In order to guarantee that node S discovers node R within D, node S must transmit probing messages every D period and its probing interval must be longer than the maximum sleeping interval of node R. Then, (a_i+b_i) becomes equal to D for all i. This requirement also leads to that $a_i > \max_{j=1,\cdots,N}(d_j)$ for all i. Then,

$$E_{total} > \sum_{i=1}^{M}(E_P \cdot \max_{j=1,..,N}(d_j) + E_S(D - \max_{j=1,..,N}(d_j))) + \sum_{j=1}^{N}(E_L \cdot c_j + E_S \cdot d_j). \quad (1)$$

III. Optimal Listening Schedule for Given Duty Cycle

For duty cycle q at node R defined as $\frac{\sum_{j=1}^{N} c_j}{\sum_{j=1}^{N}(c_j+d_j)}$, we can obtain the minimum bound for E_{total} if we can schedule sleeping intervals to satisfy

$$\min(\max_{j=1,..,N} d_j) = d, \quad (2)$$

where $d = \frac{\sum_{j=1}^{N} d_j}{N}$. (Due to space limit, we omit the proof.)

From (1) and (2),

$$\begin{aligned} E_{total} &> \sum_{i=1}^{T/D}(E_P \cdot d + E_S(D-d)) + \sum_{j=1}^{N}(E_L \cdot c_j + E_S \cdot d_j) \\ &> \frac{T^2(1-q)}{D \cdot N}(E_P - E_S) + E_S \cdot T + E_L \cdot T \cdot q + E_S \cdot T(1-q) \quad (3) \end{aligned}$$

using $d = (1-q)\frac{T}{N}$.

In (3), the bound is a function of N, the number of listening intervals in T. So, the minimum bound for E_{total} can be determined when N is maximized. Therefore, E_{total} may be minimized when we schedule every sleeping interval d_j for node R to be constant d and each probing interval a_i to be $d+\delta$. Note that δ is the smallest interval required by node R to recognize a probing message. With duty cycle q for node R, in order to maximize N, every listening interval c_i is set to δ, then $d = \frac{1-q}{q}\delta$. As a result, achievable minimum energy E_{total}^{min} is

$$\begin{aligned} E_{total}^{min} &= \sum_{i=1}^{T/D}(E_P \cdot (d+\delta) + E_S(D-d-\delta)) + \sum_{j=1}^{N}(E_L \cdot c_j + E_S \cdot d_j) \\ &= \frac{T(E_S \cdot D \cdot q - E_S \cdot \delta + E_P \cdot \delta)}{D \cdot q} + E_L \cdot T \cdot q + E_S \cdot T(1-q) \quad (4) \end{aligned}$$

using $N = \frac{Tq}{\delta}$.

IV. Optimal Duty Cycle

In previous sections, we have presented an optimal neighbor discovery scheme that discovers the adjacent nodes within D and consumes the minimum energy, but is depending on duty cycle q at node R. In this section, we introduce a method to determine the optimal duty cycle for the final step. Fig. 2 illustrates how the optimal duty cycle can be obtained. When duty cycle is small, the listening energy decreases, but the probing energy increases (Fig. 2(a)). In contrast, when duty cycle is large, the listening energy increases, but the probing energy decreases (Fig. 2(b) and (c)). It is straightforward to obtain the optimal duty cycle using the derivative and the second derivative of E_{total}^{min} with respect to q. Therefore, the optimal duty cycle is determined by

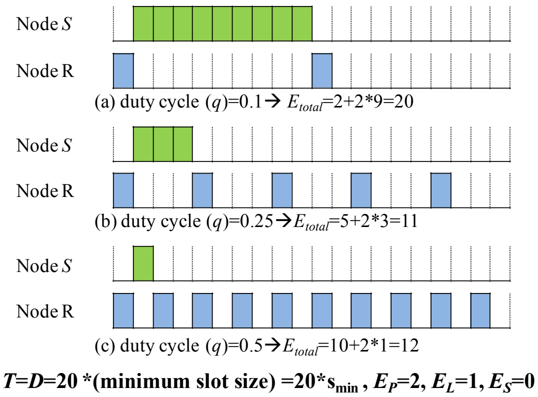

Fig. 2. Determining the optimal duty cycle

$$q_{opt} = \sqrt{\frac{(E_P - E_S)\delta}{(E_L - E_S)D}}.$$

We can illustrate that an optimal duty cycle (= 0.115499) is determined at the point where E_{total}^{min} (= $1.05541 \times 10^7\ mW$) is minimal. Each variable is respectively set to $T = 1000000 \times \delta\ ms$, $D = 100 \times \delta\ ms$, $\delta = 1\ ms$, $E_L = 4.5\ mW$, $E_S = 0.09\ mW$, and $E_P = 60\ mW$.

V. Conclusion

In this paper, we propose an optimal energy-efficient neighbor discovery scheme. The proposed scheme consumes the minimum energy and guarantees that two adjacent nodes discover each other within required delay D. The next step is to extend this result to the optimal neighbor discovery scheme for the general case.

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